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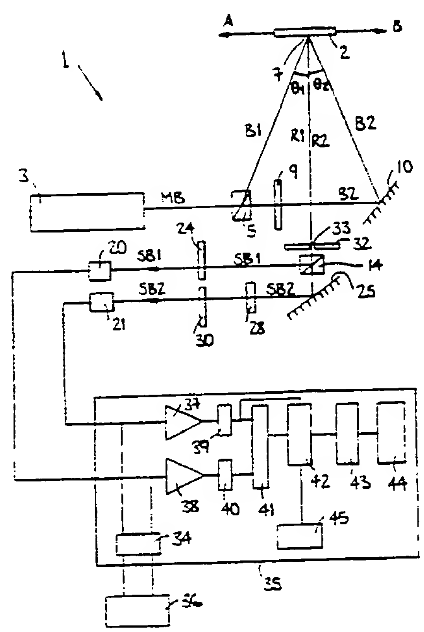
(54) Title: A METHOD AND APPARATUS FOR DETERMINING DIRECTION OF DISPLACEMENT OF AN OBJECT SURFACE

(57) Abstract

Apparatus (1) for determining direction of in-plane displacement of a surface (2) based on the principle of interferometry directs two beams of coherent light (B1) and (B2) which are orthogonally plane polarised relative to each other at the surface (2). Scattered beams (R1) and (R2) from the surface (2) are split in a beam splitter (14) into secondary beams (SB1) and (SB2). Plane polarisers (24) and (30) plane polarise the beams (SB1) and (SB2) for forming speckle interference patterns on transducers (20) and (21). A quarter wave plate (28) phase shifts one of the components in the secondary beam (SB1) by 90° relative to the other component of the secondary beam (SB1). Circuitry (35) determines the direction of phase shift of the speckle interference patterns for determining the direction of displacement of the object surface (2).



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A METHOD AND APPARATUS FOR DETERMINING DIRECTION OF DISPLACEMENT OF AN OBJECT SURFACE

Field of the Invention

The present invention relates to a method and apparatus for determining direction of displacement of an object surface using an interferometer. The invention also relates to a method and apparatus for determining displacement of the object surface.

Background to the Invention

Interferometers are commonly used for determining displacement of an object. Typically, a beam of coherent light is directed at a surface of the object and first and second speckle patterns are formed and superimposed one on the other to form a speckle interference pattern. A single speckle of the speckle interference pattern is observed and the cyclic variation in intensity of the speckle due to phase change between the first and second patterns resulting from displacement of the surface gives a measure of the distance moved by the object surface, namely, the displacement of the object surface.

Methods and apparatus for determining displacement of an object surface using an interferometer are described in European Patent Specification No. 0,024,167A. The European specification describes methods and apparatus for determining both in-plane and out-of-plane displacement of a surface.

In determining in-plane displacement, a pair of beams of coherent light are directed at the same area of the object surface and scattered. The scattered beams are combined to form an interference pattern and a single speckle of the interference pattern is observed. The number of cyclic variations in intensity of the observed speckle is counted, and the count is proportional to the in-plane displacement of the object surface.

In determining out-of-plane displacement of an object surface, one beam of coherent light is directed at the object surface and scattered, while a second beam of coherent light is directed at a

reference surface and scattered. Light scattered from the object and reference surfaces is combined to form a speckle interference pattern. By observing and counting the cyclic variation in intensity of a single speckle, the out-of-plane displacement is determined. The count of cyclic variations is proportional to the out-of-plane displacement.

While the methods and apparatus for determining in-plane and out-of-plane displacement of an object surface described in European Patent Specification No. 0,024,167A are adequate for determining the displacement, the methods and apparatus, with one exception, are incapable of determining the direction of the displacement of the object surface. One apparatus described in European Patent Specification No. 0,024,167A, while it may be used for determining the direction of displacement, is rather cumbersome, inefficient and uneconomic to produce and use.

There is therefore a need for a method and apparatus for determining direction of displacement of an object surface.

Objects of the Invention

One object of the invention is to provide a method and apparatus for determining direction of displacement of an object surface. Another object of the invention is to provide a method and apparatus for determining direction of displacement of an object surface which is relatively simple and easy to construct and use. A further object of the invention is to provide a method and apparatus for determining direction of displacement of an object surface which is relatively economical to construct and use.

Summary of the Invention

According to the invention, there is provide a method for determining direction of displacement of an object surface using an interferometer of the type in which a beam of coherent light is directed at the object surface and a speckle interference pattern is formed by combining first and second primary scattered beams, at least one of which primary scattered beams is scattered from the object surface

wherein the combined scattered beam is split into two secondary scattered beams, each secondary scattered beam comprising at least one component of light of each of the first and second primary scattered beams, one of the components of light in one of the secondary scattered beams is caused to be phase shifted relative to another component of light in that secondary scattered beam or relative to one of the components of light of the other secondary scattered beam, and the direction of the resultant phase shift of the speckle interference pattern of one of the secondary scattered beams relative to the speckle interference pattern of the other secondary scattered beam is detected for determining the direction of displacement of the object surface.

In one embodiment of the invention, the component to be phase shifted in the one of the secondary scattered beams is phase shifted relative to another component in that secondary scattered beam.

Alternatively, the component to be phase shifted in the one of the secondary scattered beams is phase shifted relative to a component in the other secondary scattered beam.

Preferably, the phase shifted component of the secondary scattered beam is phase shifted through approximately 90°. It will of course be appreciated that the phase shifted component may be phase shifted through substantially any angle, provided it is not phase shifted through 180°.

Advantageously, each secondary scattered beam is polarised prior to detecting the direction of the resultant phase shift of the speckle interference patterns.

Preferably, the direction of the resultant phase shift between the speckle interference patterns is detected by observing a single speckle of the respective speckle interference patterns. Advantageously, the same speckle is observed in each speckle interference pattern. Advantageously, the combined first and second primary scattered beams are passed through a restricting means for

permitting the passage of only one speckle therethrough prior to splitting the combined beam to form the secondary scattered beams.

In one embodiment of the invention, the component of light to be phase shifted is phase shifted in one of the secondary scattered beams after the combined beam has been split. Alternatively, the component of light to be phase shifted is phase shifted prior to scattering of the said first or second primary scattered beam.

In one embodiment of the invention, the first and second primary scattered beams are scattered from the object surface for determining the direction of in-plane displacement. Preferably, the first and second primary scattered beams are scattered from the same area on the object surface. Advantageously, the first and second primary scattered beams are derived from respective beams of coherent light directed at the object surface.

In one embodiment of the invention, each beam of coherent light is directed at the object surface at an angle of incidence in the range of 0° to 70°. Preferably, each beam of coherent light is directed at the object surface at an angle of incidence in the range of 0° to 30°. Advantageously, each beam of coherent light is directed at the object surface at an angle of incidence of approximately 20°. In determining the optimum angle of incidence, two factors must be considered. Firstly, if the angle of incidence is too small, a large displacement of the object surface is required to obtain a single cyclic variation of a speckle of a speckle interference pattern, and accordingly, the sensitivity of the apparatus to displacement is affected. While on the other hand, if the angle of incidence is too large, depolarisation of the light occurs on scattering from the object surface, which affects the reliability of the apparatus in determining the direction of displacement. Depolarisation of the light on scattering inhibits the generation of a constant phase shift between the speckle interference patterns formed by the secondary scattered beams. Using light of wavelength of the order of 546 nm permits an angle of incidence of up to approximately 30°. At such an angle using light of wavelengths of the order of 546 nm, depolarisation on scattering of

the light has been found to be approximately 4%, which is sufficiently low to permit adequate results to be achieved from the apparatus. However, with light of wavelength of the order of 546 nm and an angle of incidence of 15°, depolarisation has been found to be only 2%, which considerably improves the reliability of the apparatus in determining direction of displacement. It is, however, believed that an angle of incidence of up to 70° would be acceptable where light of wavelength of 10.6 microns is used. Such light may be derived from a carbon dioxide laser source.

Preferably, the angle of incidence at which each beam of coherent light is directed at the object surface is the same. It has been found desirable to maintain the angle of incidence of both beams of coherent light equal so that the apparatus is sensitive to displacement in one direction only. Where the angles of incidence are not equal, it has been found that results from the apparatus may be influenced by displacement of the object surface in a plane other than its own plane.

In one embodiment of the invention, the component of light to be phase shifted is phase shifted in one of the beams of coherent light prior to reaching the object surface.

Alternatively, one of the first and second scattered beams is scattered or reflected from a reference surface for determining the direction of out-of-plane displacement of the object surface, the first and second scattered beams being formed by directing respective beams of coherent light at the object and reference surfaces. Preferably, the beams of coherent light are incident at approximately 90° to the respective surfaces. Advantageously, at least one of the respective object and reference surfaces is optically rough. In one embodiment of the invention, the reference surface is optically smooth.

In one embodiment of the invention, the two beams of coherent light are derived from the same source, a main beam of coherent light from the source being split to form the said two beams. Preferably, the

main beam of coherent light is plane polarised. Advantageously, the main beam of coherent light is derived from a laser light source. Advantageously, the beam of coherent light is derived from a helium neon laser light source. Preferably, the two beams of coherent light are plane polarised.

In one embodiment of the invention, the plane of polarisation of one of the beams of coherent light is at 90° relative to the plane of polarisation of the other beam of coherent light. In an alternative embodiment of the invention, the planes of polarisation of the beams of coherent light are similar.

Advantageously, the optical path difference between the two beams of coherent light is substantially constant when determining the direction of in-plane displacement.

In one embodiment of the invention, the method further comprises the step of counting the number of cyclic variations in intensity in a speckle interference pattern for determining the displacement of the object surface. Preferably, the method further comprises the step of counting the number of cyclic variations in intensity in the speckle interference pattern in a predetermined period of time for determining the speed of displacement of the object surface.

Additionally, the invention provides apparatus for determining the direction of displacement of an object surface, the apparatus comprising an interferometer of the type comprising means for directing a beam of coherent light at the object surface and means for forming a speckle interference pattern by combining first and second primary scattered beams, at least one of the said primary scattered beams being scattered from the object surface wherein the apparatus further comprises secondary splitting means for splitting the combined scattered beam into two secondary scattered beams so that each secondary scattered beam comprises at least one component of light of each of the first and second primary scattered beams, phase shifting means for phase shifting one of the components of light of one of the secondary scattered beams relative to another component of light of

that secondary scattered beam or relative to one of the components of light of the other secondary scattered beam, and detecting means for detecting the direction of the resultant phase shift of the speckle interference pattern of one of the secondary scattered beams relative to the speckle interference pattern of the other secondary scattered beam for determining the direction of displacement of the object surface.

In one embodiment of the invention, the phase shifting means phase shifts a component in one of the secondary scattered beams relative to another component in that secondary scattered beam.

Alternatively, the phase shifting means phase shifts a component in one of the secondary scattered beams relative to a component in the other secondary scattered beam.

Preferably, the phase shifting means phase shifts the component of light to be phase shifted through an angle of approximately 90°.

In one embodiment of the invention, the means for forming the speckle interference patterns comprises a pair of secondary plane polarising means for plane polarising each of the secondary scattered beams.

In another embodiment of the invention, one of the secondary plane polarising means is mounted intermediate the phase shifting means and the detecting means.

Preferably, restricting means for permitting the passage of only one speckle of the speckle interference pattern to the detecting means is provided. Advantageously, the restricting means is mounted intermediate the secondary splitting means and the object surface.

In one embodiment of the invention, the means for directing a beam of coherent light at the object surface comprises first and second directing means for directing a pair of beams of coherent light at the object surface.

In another embodiment of the invention, the first and second directing means direct the beams of coherent light at the same area on the object surface.

Preferably, the two beams of coherent light are derived from a main light source means.

Advantageously, the main light source means provides a main beam of plane polarised coherent light.

In one embodiment of the invention, primary beam splitting means is provided for splitting the main beam of coherent light into the two beams of coherent light.

In another embodiment of the invention, the phase shifting means is provided in the path of one of the beams of coherent light before the said beam of light reaches the object surface.

Alternatively, a reference surface is provided, and the directing means comprises first and second directing means, the first directing means directing a beam of coherent light at the object surface and the second directing means directing a beam of coherent light at the reference surface. In one embodiment of the invention, one of the respective object and reference surfaces is optically rough. Preferably, the reference surface is optically smooth.

In another embodiment of the invention, means for combining the first and second primary scattered beams combines the first primary scattered beam scattered from the object surface and the second primary scattered beam scattered or reflected from the reference surface.

In another embodiment of the invention, the detecting means comprises a pair of photoelectric transducers for receiving the respective secondary scattered beams, and signal analyzing means for receiving and analyzing electronic signals received from the photoelectric transducers for determining the direction of the resultant phase shift

between the speckle interference patterns of the respective secondary scattered beams. Preferably, the apparatus further comprises means for counting the number of cyclic variations in intensity in a speckle interference pattern for determining displacement of the object surface. Advantageously, the means for determining the number of cyclic variations in intensity in the speckle interference pattern counts the number of cyclic variations in a predetermined period of time for determining the speed of displacement of the object surface.

Advantages of the Invention

The advantages of the invention are many. A particularly important advantage of the invention is that it provides a method and apparatus for determining the direction of displacement of an object surface. In certain embodiments of the invention, the method and apparatus also determines the displacement of the object surface. A particularly important advantage of the invention is that it provides a method and apparatus for determining the displacement of an object surface which is relatively simple and easy to construct and use. Another important advantage of the invention is that it provides a method and apparatus for determining direction of displacement of an object surface which is relatively economical to construct and use. The apparatus according to the invention is also less prone to error than apparatus known heretofore. The apparatus also permits a relatively low cost light source means to be used.

These and other objects and advantages of the invention will be readily apparent to those skilled in the art from the following description of some preferred embodiments thereof, which are given by way of example only.

Brief description of the drawings

Fig. 1 is a schematic representation of apparatus according to the invention for determining displacement and direction of displacement of an object surface,

Fig. 2 is a schematic representation of apparatus according to another embodiment of the invention for determining displacement

and direction of displacement of an object surface, and

Fig. 3 is a schematic representation of apparatus according to a further embodiment of the invention for determining displacement and direction of displacement of an object surface.

Detailed description of the Invention

Referring to the drawings, and initially to Fig. 1, there is illustrated apparatus according to the invention indicated generally by the reference numeral 1 for determining both displacement and direction of displacement of an optically rough object surface 2. In this embodiment of the invention, the apparatus is for determining in-plane displacement of the object surface 2, namely, displacement in the directions of the arrows A and B. The apparatus 1 operates substantially on the principle of an interferometer, and in describing the apparatus 1, it will be assumed that the reader understands the operation of an interferometer.

The apparatus 1 comprises a main light source means, in this embodiment of the invention, an unexpanded helium neon laser light source 3 of output power 10 mW. The light source 3 projects a substantially parallel main beam MB of circular cross section of coherent laser light at a primary beam splitting means, namely, a primary beam splitter 5 comprising a lossy beam splitter. The main beam MB is polarised in the vertical plane, namely, in a plane normal to the page of the drawing. The primary beam splitter 5 splits the main beam MB into two beams of coherent laser light, namely, a first beam B1 and a second beam B2. The primary beam splitter 5 acts as a first directing means and directs the first beam B1 at an area 7 of the object surface 2 at an angle of incidence θ_1 to the normal to the object surface 2. The plane of polarisation of the first beam B1 is unaltered by the primary beam splitter 5, in other words, the plane of polarisation of the first beam B1 is polarised in the vertical plane. The second beam B2 passes through the primary beam splitter 5 also polarised in the vertical plane, and is passed through a primary plane polarisation means, namely, a primary half wave plate 9 whose fast axis is at an angle of 45° to the vertical for turning the plane of

polarisation of the second beam B2 through 90°. In other words, on passing through the primary half wave plate 9 the second beam B2 is polarised in the horizontal plane, and is thus orthogonally plane polarised relative to the first beam B1. Second directing means for directing the second beam B2 at the object surface 2 comprises a reflector 10 which reflects the beam B2 to the same area 7 of the object surface 2 at which the first beam B1 is incident. The reflector 10 directs the second beam B2 at the area 7 of the object surface 2 at an angle of incidence θ_2 to the normal to the object surface 2, which in this embodiment of the invention is equal to θ_1. In this case, θ_1 and θ_2 are 20°. The reflector 10 does not alter the plane of polarisation of the beam B2.

Light from the first and second beams B1 and B2 is scattered by the object surface 2. A first primary scattered beam R1 and a second primary scattered beam R2 which are derived respectively from the first and second beams B1 and B2 which are scattered by the object surface 2 combine to form a combined beam which passes along the normal from the object surface 2 to a secondary beam splitting means, namely, a secondary beam splitter 14 comprising a lossy beam splitter. The secondary beam splitter 14 splits the combined first and second primary scattered beams R1 and R2 into a pair of secondary scattered beams, namely, a first secondary scattered beam SB1 and a second secondary scattered beam SB2 both of which will be described below. The first and second primary scattered beams R1 and R2 remain polarised after being scattered and remain polarised in the same plane of polarisation as their respective corresponding first and second beams B1 and B2. Accordingly, the first and second primary scattered beams R1 and R2 are orthogonally plane polarised relative to each other and do not interfere with each other. The combined first and second primary scattered beams R1 and R2 are split in the secondary beam splitter 14 so that each of the first and second secondary scattered beams SB1 and SB2 comprise the first and second primary scattered beams R1 and R2. Thus, each secondary scattered beam SB1 and SB2 has a vertical and horizontal component of light derived respectively from the first and second primary scattered beams R1 and R2.

The first and second secondary scattered beams SB1 and SB2 are directed at detecting means, which in this case comprises a pair of first and second photoelectric sensitive transducers 20 and 21, the purpose of which is described below. The first secondary scattered beam SB1 is directed at the first transducer 20 through a means for forming a speckle interference pattern, which is provided by a first secondary plane polarising means, namely, a first plane polarising plate 24. The transmission axis of the first plane polarising plate 24 is at 45° to the two planes of polarisation of the first and second primary scattered beams R1 and R2 for forming a speckle interference pattern by combining the first and second primary scattered beams R1 and R2 in the first secondary scattered beam SB1. The speckle interference pattern is received by the first transducer 20. The second secondary scattered beam SB2 is reflected through 90° from a reflector 25 and passed through a phase shifting means for phase shifting one of the components of the light in the second secondary scattered beam SB2 through 90° relative to the other component in that secondary scattered beam SB2. The phase shifting means comprises a quarter wave plate 28 whose fast axis is parallel to the plane of polarisation of one of the components of light of the second secondary scattered beam SB2, in this case, the vertical component. Thus, the quarter wave plate 28 phase shifts the vertical component through 90° relative to the horizontal component of the second secondary scattered beam SB2. The second secondary scattered beam SB2 passes from the quarter wave plate 28 into a means for forming a speckle interference pattern which is provided by a second secondary plane polarising means comprising a second plane polarising plate 30. The transmission axis of the second plane polarising plate 30 is at 45° to the two planes of polarisation of the first and second primary scattered beam components of the second secondary scattered beam SB2 for forming a speckle interference pattern which is received by the second transducer 21.

Due to the phase shifting action of the quarter wave plate 28 on the second secondary scattered beam SB2, the speckle interference pattern falling on the second transducer 21 is phase shifted by 90° relative to the speckle interference pattern falling on the first transducer 20.

Restricting means for permitting the passage of only one speckle of a speckle interference pattern to fall on the first and second transducers 20 and 21 comprises a pin hole plate 32 having a pin hole 33 of diameter sufficiently small to permit only a single speckle of a speckle interference pattern to pass therethrough, thereby the transducers 20 and 21 detect the image of the same speckle of the speckle interference pattern.

By determining the direction of the resultant phase shift between the speckle interference patterns formed by the first and second secondary scattered beams SB1 and SB2, the direction of displacement of the object surface 2 is determined. A change in direction of the object surface 2 causes a change in the direction of the resultant phase shift. In other words, when the phase of the speckle interference pattern formed by the second secondary scattered beam SB2 leads the speckle interference pattern formed by the first secondary scattered beam SB1, the object surface 2 is moving in the direction of the arrow A. When the phase of the speckle interference pattern formed by the second secondary scattered beam SB2 lags the speckle interference pattern formed by the first secondary scattered beam SB1, the object surface 2 is moving in the direction of the arrow B. Accordingly, by observing the cyclic variation in intensity of the speckle falling on the first and second transducers 20 and 21, the direction of the resultant phase shift (in other words the sign of the phase difference) of the speckle interference patterns of the first and second secondary scattered beams SB1 and SB2 is determined.

The means for detecting the direction of the resultant phase shift of the speckle interference patterns, as well as comprising the first and second transducers 20 and 21, also comprises signal analyzing means provided by an electronic analyzing circuit 35 for analyzing electronic signals received from the transducers 20 and 21 and for providing results. The circuit 35 comprises a buffer circuit 34 for delivering the signals from the transducers 20 and 21 to a display unit 36 for displaying the direction of the resultant phase shift. The display unit 36 may be a graph plotter or a cathode ray oscilloscope or other suitable display device, which would give a

visual representation of the signals received from the transducers 20 and 21. The direction of the resultant phase shift between the signals received from the transducers 20 and 21 may be visually observed on the display unit 36. Accordingly, by observing the direction of the resultant phase shift of the signals, the direction of the displacement of the object surface 2 can readily easily be determined. Alternatively, if desired, the signals from the transducers 20 and 21 may be fed to further analyzing circuitry (not shown) which would give a numerical indication of the direction of the resultant phase shift.

The in-plane displacement of the object surface 2 is proportional to the number of cyclic variations of intensity of the speckle falling on either the first or second transducer 20 and 21. Accordingly, by counting the number of cyclic variations of intensity of the observed speckle, the displacement of the object surface 2 can be determined. The signals from the transducers 20 and 21 are passed to operational amplifier circuits 37 and 38 which amplify the signals. The outputs from the amplifier circuits 37 and 38 are passed to Schmitt trigger circuits 39 and 40 which convert the signals to rectangular pulses which are fed to a dual edge triggered D-type flip flop circuit 41 to provide count up/count down commands to a counter 42 which also receives rectangular pulses from the Schmitt trigger circuit 39. Signals from the counter 42 are delivered to a correlation circuit 43 which correlates the number of counts of cyclic variation of the intensity of the speckle to a corresponding value of displacement of the object surface in either direction of the arrows A or B. The output from the correlation circuit 43 is delivered to a display 44 which displays the displacement of the object surface 2. A timer 45 permits the number of counts from the Schmitt trigger circuit 39 in a predetermined period of time to be counted to enable the speed of displacement of the object surface 2 to be computed. The speed is also displayed on the display 44.

In this embodiment of the invention, to ensure that only a single speckle of the speckle interference pattern passes through the pinhole 33 of the pinhole plate 32, the diameter of the pinhole 33 is 650 μm

diameter and the pinhole plate 32 is placed at approximately 680 mm from the object surface 2.

The optical path difference between the two beams B1 and B2 remains substantially constant during tests, apart from the effect of any slight variations in the surface profile of the object surface 2.

Referring now to Fig. 2, there is illustrated apparatus according to another embodiment of the invention indicated generally by the reference numeral 50 also for determining in-plane displacement and direction of displacement of an optically rough object surface 2. The apparatus 50 in certain respects is similar to the apparatus 1 and similar components are identified by the same reference numerals. The main beam MB from the laser light source 3 is split by the primary beam splitter 5 into first and second beams B1 and B2. The first beam is directed by the primary beam splitter 5 at an area 7 on the object surface 2, while the second beam B2 is reflected by the reflector 10 to the same area 7 of the object surface 2. The angle of incidence of the two beams B1 and B2 to the normal of the object surface 2, namely θ_1 and θ_2 are equal and equal to 20°. The main beam MB from the light source 3 is plane polarised in the vertical plane. The first and second beams B1 and B2 leave the primary beam splitter 5 plane polarised in the vertical plane. Means for altering the plane of polarisation of the first and second beams B1 and B2 comprise a pair of half wave plates 53 and 54, each of which have a fast axis at 22.5° to the vertical. The half wave plates 53 and 54 rotate the plane of polarisation of the first and second beams B1 and B2 by 45° so that the plane of polarisation of the first and second beams B1 and B2 leaving the half wave plates 53 and 54 is at 45° to the vertical and horizontal axes. The first beam B1 is passed through a phase shifting means, namely, a quarter wave plate 56, the fast axis of which is vertical. The quarter wave plate 56 phase shifts the vertical component of the beam B1 relative to the horizontal component of the beam B1. Accordingly, the vertical component of the first beam B1 falls on the object surface 2 out of phase by 90° relative to the horizontal component of the first beam B1. The beams B1 and B2 are scattered by the object surface 2 and a combined beam comprising first

and second primary scattered beams R1 and R2 derived respectively from the beams B1 and B2 is passed to the secondary beam splitter 14. The vertical component of the first primary scattered beam R1 is 90° out of phase with the horizontal component of the first primary scattered beam R1.

The secondary beam splitter 14 splits the combined first and second primary scattered beams R1 and R2 into first and second secondary scattered beams SB1 and SB2. The secondary beam splitter 14 splits the combined scattered beam so that the vertical components of the first and second primary scattered beams R1 and R2 are in the first secondary scattered beam SB1, and the horizontal components of the first and second primary scattered beams R1 and R2 are in the second secondary scattered beam SB2. The first secondary scattered beam SB1 is thus vertically polarised and comprises two vertical components which are derived from the vertical components of the first and second primary scattered beams R1 and R2. Additionally, the vertical components of the first secondary scattered beam SB1 interfere with each other to form a speckle interference pattern. The second secondary scattered beam SB2 is horizontally polarised and comprises two horizontal components which are derived from the horizontal components of the first and second primary scattered beams R1 and R2, which also interfere with each other to form a speckle interference pattern. The vertical component of the first secondary scattered beam SB1 which is derived from the first primary scattered beam R1 is 90° out of phase of the horizontal component derived from the first primary scattered beam R1 in the second secondary scattered beam SB2. A reflector 57 reflects the first secondary scattered beam SB1 onto the first transducer 20 while the second secondary scattered beam SB2 is directed directly to the second transducer 21. The pinhole plate 32 only permits the passage of a single speckle of the speckle interference pattern of the combined primary scattered beams R1 and R2 to pass through to the secondary beam splitter 14, thereby ensuring that only one speckle of the speckle interference pattern falls on the transducers 20 and 21, and each transducer 20 and 21 receives the same speckle.

By virtue of the fact that one of the vertical components of the first secondary scattered beam SB1 is out of phase by 90° with the corresponding horizontal component of the second secondary scattered beam SB2, the speckle interference patterns formed by the first and second secondary scattered beams SB1 and SB2 are also out of phase by 90°. By determining the direction of the resultant phase shift between the speckle interference patterns formed by the first and second secondary scattered beams SB1 and SB2, the direction of displacement of the object surface 2 is determined. When the phase of the speckle interference pattern formed by the first secondary scattered beam SB1 leads the phase of the speckle interference pattern formed by the second secondary scattered beam SB2, the object surface 2 is moving in the direction of the arrow A. When the phase of the speckle interference pattern formed by the first secondary scattered beam SB1 lags the phase of the speckle interference pattern formed by the second secondary scattered beam SB2, the object surface is moving in the direction of the arrow B.

Signals from the transducers 20 and 21 are delivered to the circuit 35 which is identical to the circuit 35 of the apparatus 1 for determining the direction of the resultant phase shift for determining the direction of displacement of the object surface 2, and also for determining the displacement and speed of displacement of the object surface 2.

Referring now to Fig. 3, there is illustrated apparatus according to a further embodiment of the invention indicated generally by the reference numeral 60 for determining out-of-plane displacement in the direction of the arrows C and D of an object surface 2 and also for determining the direction of the out-of-plane displacement of the object surface 2.

The apparatus 60, while not being identical to the apparatus 1, comprises a number of components which are substantially similar to the apparatus 1, and accordingly, similar components are identified by the same reference numerals. In this case, the main beam MB of plane polarised laser light polarised in the vertical plane from the light

source 3 is delivered to the primary beam splitter 5 through a semi-reflector 61, the purpose of which will be described below. The main beam MB passes through the semi-reflector 61 with its plane of polarisation unaltered. The main beam MB is split in the primary beam splitter 5 into two beams B1 and B2. The primary beam splitter 5 is a lossy beam splitter. The first beam B1 is directed towards an area 7 on the object surface and remains plane polarised in the vertical plane, in other words normal to the plane of the page of the drawing. The second beam B2 is plane polarised in the vertical plane and is directed towards a reference surface 63 which may be rough or smooth. The first and second beams B1 and B2 are incident at right angles on the object surface 2 and reference surface 63, respectively. Light is scattered from the object surface 2 and may be scattered or reflected from the reference surface 63, and remains polarised in the original plane of polarisation of the first and second beams B1 and B2. A first primary scattered beam R1 scattered from the object surface 2 and a second primary scattered beam R2 which may be scattered or reflected from the reference surface 63 are combined in the primary beam splitter 5 and substantially simultaneously split into first and second secondary scattered beams SB1 and SB2. Thus, in this embodiment of the invention, the primary beam splitter 14 also acts as a secondary beam splitter. The first secondary scattered beam SB1 comprises components of the first and second primary scattered beams R1 and R2 and is directed to the first transducer 20. The second secondary scattered beam SB2 comprises components of the first and second primary scattered beams R1 and R2, and is directed towards the semi-reflector 61. The semi-reflector 61 reflects the second secondary scattered beam SB2 to the second transducer 21.

The primary beam splitter 5 phase shifts the components of the first secondary scattered beam SB1 relative to each other, and also phase shifts the components of the second secondary scattered beam SB2 relative to each other. The net effect of the phase shifting of the components of the two secondary scattered beams SB1 and SB2 is that the first secondary scattered beam SB1 is phase shifted through approximately 90° relative to the second secondary scattered beam SB2. By determining the direction of the resultant phase shift between the

speckle interference patterns formed by the first and second secondary scattered beams SB1 and SB2, the direction of out-of-plane displacement in the direction of the arrows C and D of the object surface 2 is determined. This is achieved in similar fashion to the method for determining the displacement of the object surface 2 using the apparatus 1 and 2 already described.

In this embodiment of the invention, a pair of pinhole plates 32 are provided with pinholes 33 of diameter sufficient to permit only a single speckle of the speckle interference pattern to fall on the first and second transducers 20 and 21. The pinhole plates 32 are arranged so that the same speckle is detected by both transducers 20 and 21. It is envisaged in certain cases that a pinhole plate may be provided in the primary beam splitter 5 to further ensure that an image of the same speckle falls on the first and second transducers 20 and 21.

The circuit 35, which is identical to the circuit 35 of the apparatus 1, determines whether the direction of the resultant phase shift is leading or lagging. A leading phase shift of the speckle interference pattern formed by the first secondary scattered beam SB1 relative to the speckle interference pattern formed by the second secondary scattered beam SB2 indicates out-of-plane displacement of the object surface 2 in the direction of the arrow C, while a lagging phase shift indicates displacement of the object surface 2 in the direction of the arrow D.

In the case of the apparatus of Figs. 1 and 2, it has been found that for aluminium surfaces, light of wavelength 546 nm provides particularly good results where the angle of incidence of the beam of coherent light on the object surface is maintained within the range 0° to 30°. It has been found that the difference in reflectances of the horizontal and vertical components of the first and second beams incident on the object surface is 4% maximum. Accordingly, for an angle of incidence of 15°. the depolarisation has been found to be only 2%, which is believed to be insufficient to cause any problems in producing reliable phase quadrature signals in the transducers. It is

believed that where an object surface of steel is provided, a light source of wavelength of 633 nm is adequate, provided the angle of incidence of the first and second beams of coherent light on the object surface is relatively small. It is envisaged that the smaller the angle of incidence, the lower the resolution of the transducer, though this can be overcome by improving the interpolation of the electronic signals.

While the light source has been described as being provided by a particular type of laser light source, any other suitable laser light source may be used. Indeed, in certain cases, it is envisaged that a laser diode type light source may be used. Further, it is envisaged that light sources other than a laser light source may be provided. Any light source which provides a coherent light beam over a sufficient distance which will be well known to those skilled in the art would be suitable. While the light source has been described as providing a beam of circular cross section, a beam of any other cross section may be provided.

While the primary and secondary beam splitting means have been described as being provided by lossy beam splitters, any other suitable beam splitters may be used. Indeed, it is envisaged in certain cases that the primary beam splitter may be dispensed with if a pair of independent light sources were provided. Other suitable phase shifting means besides quarter wave plates may be used, and in the case of the apparatus of Fig. 3, a phase shifting means independent of the primary beam splitter may be provided for phase shifting one of the secondary scattered beams relative to the other.

It will of course be appreciated that in order to determine in-plane or out-of-plane displacement of the object surface, it is only necessary to count one of the cyclic variations of intensity of the speckle received by one of the transducers.

The apparatus described with reference to Figs. 1 to 3, as well as being used for determining linear displacement and the direction of displacement of an object surface, may also be used for determining

the rotational displacement and direction of an object surface.

It is also envisaged that a polarisation preserving fibre-optic light guide may be located with one end on the object surface normal at a distance from the object surface of at least z

$$\text{where } z = r\, w / (1.5\, \lambda)$$

with w now the core diameter of the fibre, r the diameter of the illuminated spot on the object surface and λ the source wavelength. The fast axis of the fibre at the input end would be set parallel to the plane of polarisation of the laser. This would provide for a compact system.

It is further envisaged that two polarisation preserving fibres may be used, whose input ends would be oriented with their fast axes parallel to the plane of polarisation of the main light beam and located at the object surface normal such that a single speckle more than covers both fibre end faces. The fast axes at the output ends would be oriented each at 45° to the transmission axis of a plane polariser. No beam splitter would be required. If the fibres had the same length, then a quarter wave plate would be needed as before for phase shifting, but this can be removed if the fibres differ in length by a quarter of a beatlength. Furthermore, in the case of in-plane motion of an object surface, the light scattered from the object surface along the normal to the object surface may be passed into a polarisation preserving fibre coupler, whose fast axis is parallel to the plane of polarisation of the laser, and whose output fibres differ in length by one quarter of a beatlength, and the quarter wave plate could be dispensed with.

It is also envisaged that where the source light is plane polarised at 45° to the horizontal, that is the plane of the apparatus, a quarter wave plate known as an input quarter wave plate may be inserted between the beam splitter and the object in the apparatus of Fig. 2. The quarter wave plate would have its fast axis parallel to the plane polarisation direction. The plane polarisers and output quarter wave plate can be dispensed with in this arrangement and replaced by a single polarising beam splitter.

It will be appreciated that the apparatus of the invention may, if desired, be enclosed in a housing which would be provided with a relatively small opening or window to allow illumination of the object surface and reception of the scattered beam or beams from the object surface. Advantageously, this provides for the elimination of errors arising from air currents.

While in all embodiments of the invention described, only a single speckle was observed by the transducers, it is envisaged that where the diameter of the pinhole provides an aperture three or more times greater than the speckle passing through the pinhole, it may be possible to maintain the fixed phase relationship between the signals for short displacements of approximately 100 µm.

In the case of the apparatus of Fig. 3, it is envisaged that only one of the object surface or reference surface need be optically rough. In other words, one of the object or reference surfaces could be optically smooth. In many cases, it may be preferable to provide the object surface as being optically rough and the reference surface optically smooth. The advantage of this is that it facilitates alignment of the apparatus, so that the same speckle is observed by the two transducers.

Needless to say, it will be appreciated that other beam splitting means besides a lossy beam splitter may be used, and in the case of the apparatus of Fig. 3, likewise, other beam splitting means and phase shifting means besides a lossy beam splitter may be used.

It is also envisaged that the half wave plate 9, instead of being disposed between the primary beam splitter and the reflector, may be disposed between the reflector and the object surface in the path of the second beam of coherent light B2.

CLAIMS

1. A method for determining direction of displacement of an object surface using an interferometer of the type in which a beam of coherent light is directed at the object surface and a speckle interference pattern is formed by combining first and second primary scattered beams, at least one of which primary scattered beams is scattered from the object surface characterised in that the combined scattered beam is split into two secondary scattered beams, each secondary scattered beam comprising at least one component of light of each of the first and second primary scattered beams, one of the components of light in one of the secondary scattered beams is caused to be phase shifted relative to another component of light in that secondary scattered beam or relative to one of the components of light of the other secondary scattered beam, and the direction of the resultant phase shift of the speckle interference pattern of one of the secondary scattered beams relative to the speckle interference pattern of the other secondary scattered beam is detected for determining the direction of displacement of the object surface.

2. A method as claimed in Claim 1 characterised in that the component to be phase shifted in the one of the secondary scattered beams is phase shifted relative to another component in that secondary scattered beam.

3. A method as claimed in Claim 1 characterised in that the component to be phase shifted in the one of the secondary scattered beams is phase shifted relative to a component in the other secondary scattered beam.

4. A method as claimed in Claim 1 characterised in that the phase shifted component of the secondary scattered beam is phase shifted through approximately 90°.

5. A method as claimed in Claim 1 characterised in that each secondary scattered beam is polarised prior to detecting the direction of the resultant phase shift of the speckle interference patterns.

6. A method as claimed in Claim 1 characterised in that the direction of the resultant phase shift between the speckle interference patterns is detected by observing a single speckle of the respective speckle interference patterns.

7. A method as claimed in Claim 6 characterised in that the same speckle is observed in each speckle interference pattern.

8. A method as claimed in Claim 7 characterised in that the combined first and second primary scattered beams are passed through a restricting means for permitting the passage of only one speckle therethrough prior to splitting the combined beam to form the secondary scattered beams.

9. A method as claimed in Claim 1 characterised in that the component of light to be phase shifted is phase shifted in one of the secondary scattered beams after the combined beam has been split.

10. A method as claimed in Claim 1 characterised in that the component of light to be phase shifted is phase shifted prior to scattering of the said first or second primary scattered beam.

11. A method as claimed in Claim 1 characterised in that the first and second primary scattered beams are scattered from the object surface for determining the direction of in-plane displacement.

12. A method as claimed in Claim 11 characterised in that the first and second primary scattered beams are scattered from the same area on the object surface.

13. A method as claimed in Claim 12 characterised in that the first and second primary scattered beams are derived from respective beams of coherent light directed at the object surface.

14. A method as claimed in Claim 13 characterised in that each beam of coherent light is directed at the object surface at an angle of incidence in the range of 0° to 70°.

15. A method as claimed in Claim 14 characterised in that each beam of coherent light is directed at the object surface at an angle of incidence in the range of 0° to 30°.

16. A method as claimed in Claim 15 characterised in that each beam of coherent light is directed at the object surface at an angle of incidence of approximately 20°.

17. A method as claimed in Claim 13 characterised in that the angle of incidence at which each beam of coherent light is directed at the object surface is the same.

18. A method as claimed in Claim 11 characterised in that the component of light to be phase shifted is phase shifted in one of the beams of coherent light prior to reaching the object surface.

19. A method as claimed in Claim 1 characterised in that one of the first and second scattered beams is scattered or reflected from a reference surface for determining the direction of out-of-plane displacement of the object surface, the first and second scattered beams being formed by directing respective beams of coherent light at the object and reference surfaces.

20. A method as claimed in Claim 19 characterised in that the beams of coherent light are incident at approximately 90° to the respective surfaces.

21. A method as claimed in Claim 19 characterised in that at least one of the respective object and reference surfaces is optically rough.

22. A method as claimed in Claim 21 characterised in that the reference surface is optically smooth.

23. A method as claimed in any of Claims 13 to 22 characterised in that the two beams of coherent light are derived from the same source, a main beam of coherent light from the source being split to form the

said two beams.

24. A method as claimed in Claim 23 characterised in that the main beam of coherent light is plane polarised.

25. A method as claimed in Claim 23 characterised in that the main beam of coherent light is derived from a laser light source.

26. A method as claimed in Claim 25 characterised in that the beam of coherent light is derived from a helium neon laser light source.

27. A method as claimed in Claim 23 characterised in that the two beams of coherent light are plane polarised.

28. A method as claimed in Claim 27 characterised in that the plane of polarisation of one of the beams of coherent light is at 90° relative to the plane of polarisation of the other beam of coherent light.

29. A method as claimed in Claim 27 characterised in that the planes of polarisation of the beams of coherent light are similar.

30. A method as claimed in Claim 1 characterised in that the optical path difference between the two beams of coherent light is substantially constant when determining the direction of in-plane displacement.

31. A method as claimed in Claim 1 characterised in that the method further comprises the step of counting the number of cyclic variations in intensity in a speckle interference pattern for determining the displacement of the object surface.

32. A method as claimed in Claim 31 characterised in that the method further comprises the step of counting the number of cyclic variations in intensity in the speckle interference pattern in a predetermined period of time for determining the speed of displacement of the object surface.

33. Apparatus for determining the direction of displacement of an object surface (2), the apparatus comprising an interferometer of the type comprising means for directing a beam of coherent light (3) at the object surface (2) and means for forming a speckle interference pattern by combining first and second primary scattered beams, at least one of the said primary scattered beams being scattered from the object surface characterised in that the apparatus further comprises secondary splitting means (14) for splitting the combined scattered beam into two secondary scattered beams so that each secondary scattered beam comprises at least one component of light of each of the first and second primary scattered beams, phase shifting means (28,56,5) for phase shifting one of the components of light of one of the secondary scattered beams relative to another component of light of that secondary scattered beam or relative to one of the components of light of the other secondary scattered beam, and detecting means (20,21) for detecting the direction of the resultant phase shift of the speckle interference pattern of one of the secondary scattered beams relative to the speckle interference pattern of the other secondary scattered beam for determining the direction of displacement of the object surface.

34. Apparatus as claimed in Claim 33 characterised in that the phase shifting means (28,56,5) phase shifts a component in one of the secondary scattered beams relative to another component in that secondary scattered beam.

35. Apparatus as claimed in Claim 33 characterised in that the phase shifting means (28,56,5) phase shifts a component in one of the secondary scattered beams relative to a component in the other secondary scattered beam.

36. Apparatus as claimed in Claim 33 characterised in that the phase shifting means (28,56,5) phase shifts the component of light to be phase shifted through an angle of approximately 90°.

37. Apparatus as claimed in Claim 33 characterised in that the means for forming the speckle interference patterns comprises a pair of

secondary plane polarising means (24,30) for plane polarising each of the secondary scattered beams.

38. Apparatus as claimed in Claim 37 characterised in that one of the secondary plane polarising means (30) is mounted intermediate the phase shifting means (28) and the detecting means (21).

39. Apparatus as claimed in Claim 33 characterised in that restricting means (32) for permitting the passage of only one speckle of the speckle interference pattern to the detecting means (20,21) is provided.

40. Apparatus as claimed in Claim 39 characterised in that the restricting means (32) is mounted intermediate the secondary splitting means (14) and the object surface (2).

41. Apparatus as claimed in Claim 33 characterised in that the means (5,10) for directing a beam of coherent light at the object surface (2) comprises first and second directing means (5,10) for directing a pair of beams of coherent light at the object surface (2).

42. Apparatus as claimed in Claim 41 characterised in that the first and second directing means (5,10) direct the beams of coherent light at the same area (7) on the object surface (2).

43. Apparatus as claimed in Claim 41 characterised in that the two beams of coherent light are derived from a main light source means (3).

44. Apparatus as claimed in Claim 43 characterised in that the main light source means (3) provides a main beam of plane polarised coherent light.

45. Apparatus as claimed in Claim 44 characterised in that primary beam splitting means (5) is provided for splitting the main beam of coherent light into the two beams of coherent light.

46. Apparatus as claimed in Claim 41 characterised in that the phase shifting means (56) is provided in the path of one of the beams of coherent light before the said beam of light reaches the object surface (2).

47. Apparatus as claimed in Claim 33 characterised in that a reference surface (63) is provided, and the directing means (5) comprises first and second directing means (5), the first directing means (5) directing a beam of coherent light at the object surface (2) and the second directing means (5) directing a beam of coherent light at the reference surface (63).

48. Apparatus as claimed in Claim 47 characterised in that one of the respective object and reference surfaces (2,63) is optically rough.

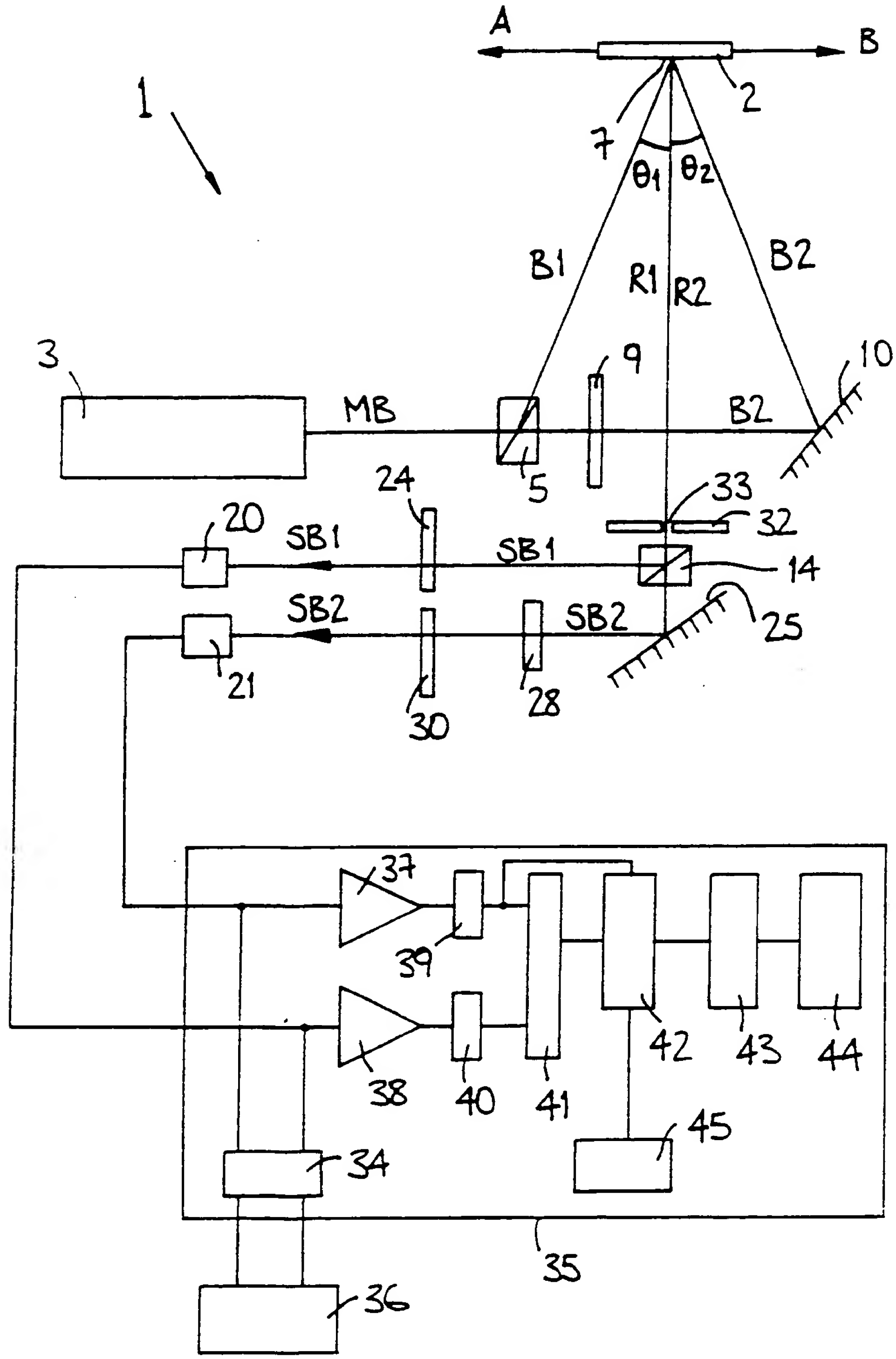
49. Apparatus as claimed in Claim 47 characterised in that the reference surface (63) is optically smooth.

50. Apparatus as claimed in Claim 47 characterised in that the means (5) for combining the first and second primary scattered beams combines the first primary scattered beam scattered from the object surface and the second primary scattered beam scattered or reflected from the reference surface (2).

51. Apparatus as claimed in Claim 33 characterised in that the detecting means (20,21) comprises a pair of photoelectric transducers (20,21) for receiving the respective secondary scattered beams, and signal analyzing means (35) for receiving and analyzing electronic signals received from the photoelectric transducers (20,21) for determining the direction of the resultant phase shift between the speckle interference patterns of the respective secondary scattered beams.

52. Apparatus as claimed in Claim 51 characterised in that the apparatus further comprises means (35) for counting the number of cyclic variations in intensity in a speckle interference pattern for determining displacement of the object surface (2).

53. Apparatus as claimed in Claim 52 characterised in that the means (35) for determining the number of cyclic variations in intensity in the speckle interference pattern counts the number of cyclic variations in a predetermined period of time for determining the speed of displacement of the object surface (2).



A
B
1
2
7
θ1
θ2
B1
R1
R2
B2
3
9
10
MB
B2
24
5
33
20
32
SB1
SB1
14
SB2
SB2
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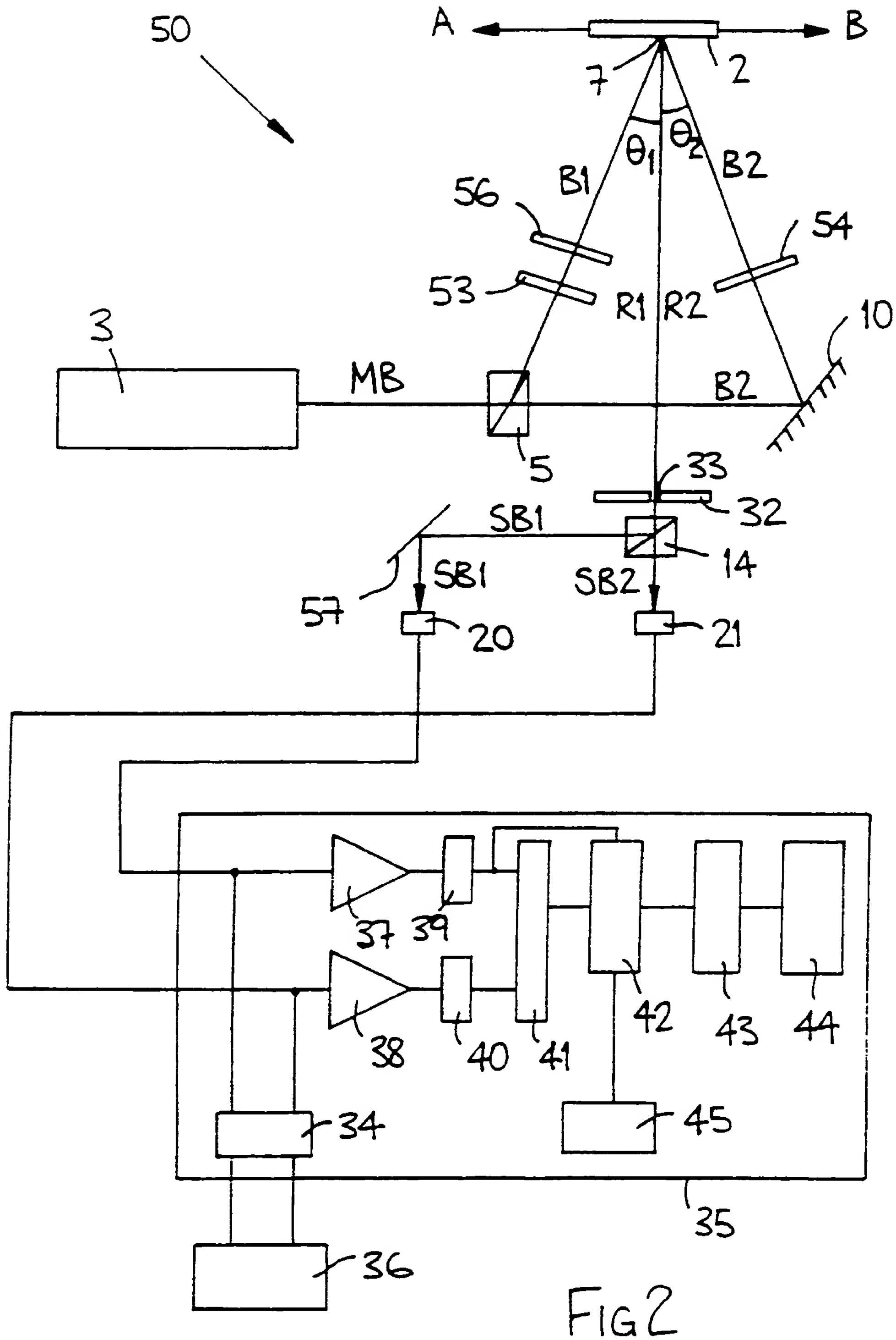
FIG 1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B
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7
θ1
θ2
B1
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54
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R1
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5
33
32
SB1
14
SB1
SB2
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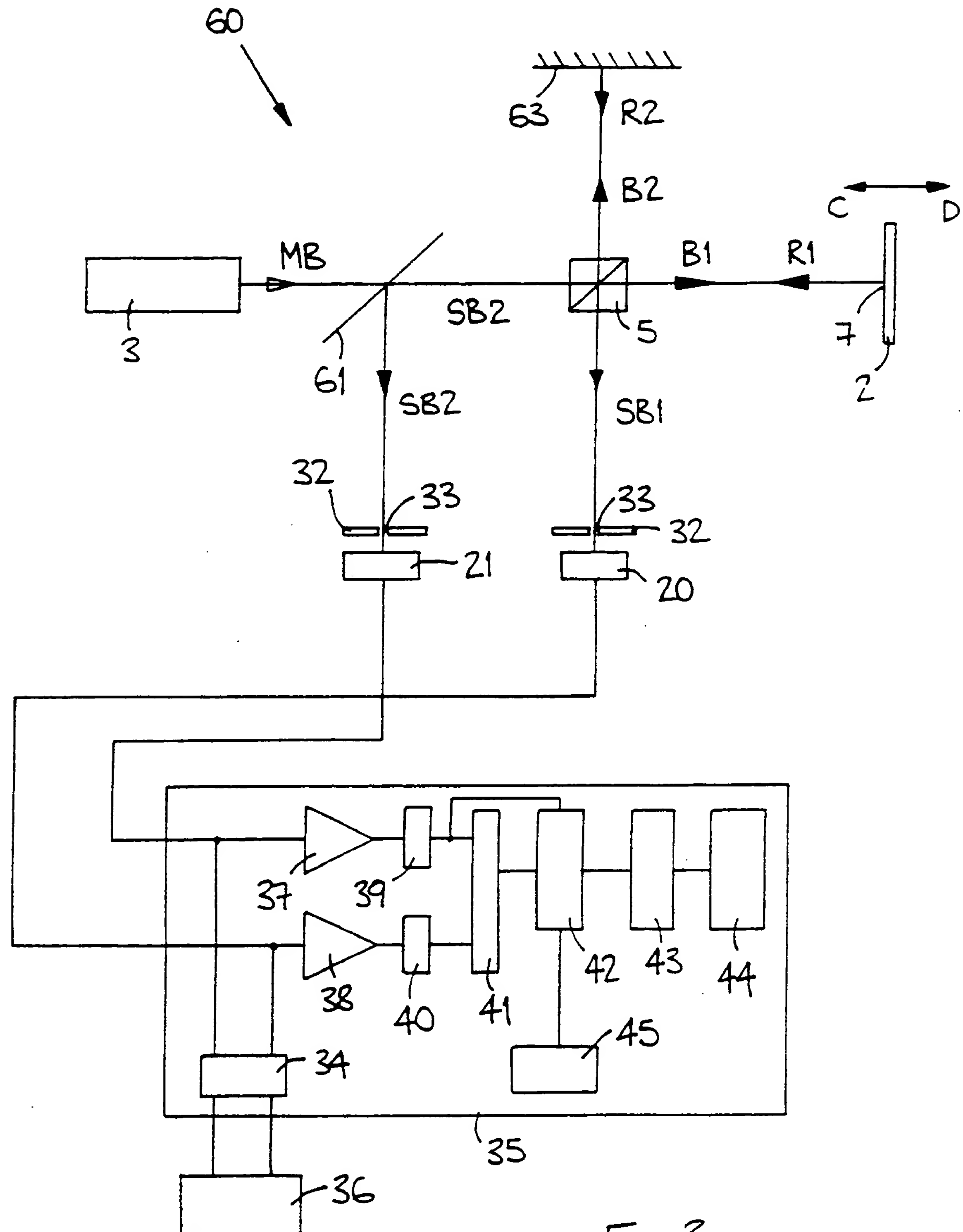
FIG 2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63
R2
B2
C
D
MB
B1
R1
SB2
5
7
3
61
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SB2
SB1
32
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FIG 3

INTERNATIONAL SEARCH REPORT

International Application No PCT/GB 92/00186

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.Cl. 5 G01B9/02; G01B11/16

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
Int.Cl. 5	G01B

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched[8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category °	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No.[13]
X	PATENT ABSTRACTS OF JAPAN vol. 8, no. 82 (P-268)(1519) 14 April 1984 & JP,A,58 225 304 (YOKOGAWA DENKI SEISAKUSHO K.K.) 27 December 1983	1,5-7, 11,19, 20,23, 24,27, 28,31 33,37, 39,47, 50-52
A		21,22, 24-27, 32,43, 45,46, 48,49 53
	see abstract ---	

-/--

° Special categories of cited documents : [10]

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
29 APRIL 1992	29. 05. 92
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	VISSER F.P.C.

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)		
Category °	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No.
X	PATENT ABSTRACTS OF JAPAN vol. 12, no. 2 (P-652)(2849) 7 January 1988 & JP,A,62 165 104 (MITSUBISHI HEAVY IND. LTD.) 21 July 1987	1,5-7, 11-13, 17,31, 33,37, 41,42, 51,52
A	see abstract	14-16, 25-28, 30,32,53
A	PATENT ABSTRACTS OF JAPAN vol. 9, no. 54 (P-340)(1777) 8 March 1985 & JP,A,59 190 605 (HITACHI SEISAKUSHO K.K.) 29 October 1984 see abstract	1,6,7, 10-18, 23-30, 33,41-46
A	PATENT ABSTRACTS OF JAPAN vol. 8, no. 82 (P-268)(1519) 14 April 1984 & JP,A,58 225 303 (YOKOGAWA DENKI SEISAKUSHO K.K.) 27 December 1983 see abstract	1,6-8, 19, 23-29, 33,39, 40,51-53
A	PATENT ABSTRACTS OF JAPAN vol. 8, no. 82 (P-268)(1519) 14 April 1984 & JP,A,58 225 302 (YOKOGAWA DENKI SEISAKUSHO K.K.) 27 December 1983 see abstract	1,6-8, 19, 23-29, 33,39, 40,51-53